

## VIBRATION INDUCED PERPETUAL ENERGY RESOURCE

### CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a divisional of United States Patent  
5 Application No. 10/124,049 filed on April 17, 2002, the disclosure of which is  
incorporated herein by reference.

### FIELD OF THE INVENTION

[0002] The present invention relates generally to piezoelectric devices  
10 which generate electrical energy by induced vibration and more specifically to an  
apparatus and method to utilize a thin, conformable sheet, having a plurality of  
piezobimorph cantilevered beams to produce electrical energy.

### BACKGROUND OF THE INVENTION

15 [0003] Moving objects or platforms generate vibration energy which is  
commonly steady in amplitude or that increases with age of the object or  
platform. All platforms suffer material degradation over time due to this  
continuous vibration, and for this reason system inspections are periodically  
performed or sensors are installed to monitor strain levels in such structures to  
20 help predict material failure. Common remotely addressable sensor devices  
require a power level in the milliwatt (mW) range. Batteries or other fuel sources  
can power such sensing devices. These power sources have drawbacks in that  
they require frequent maintenance or replacement, and in many instances may  
be located in difficult to reach locations in a platform. In addition, they deliver  
25 inadequate power levels and often fail at low temperature extremes.

[0004] Devices which generate mechanical or electrical power by the vibration of the item to which they are attached are known. In an exemplary application, the proof mass used in automatic wrist watches, i.e., the self-winding wrist watches, either rotates or moves in one direction due to the movement of the wearer's wrist. This type of device produces energy in very low quantities, typically in the micro-watt range, sufficient to power the wrist watch. Based on its low power output and form factor, this type of device is not desirable for a power source for remote sensing devices required on applications for moving platforms such as aircraft. Further, this type of proof mass system is more suitable for impulse movements as opposed to continuous vibration movements. In addition, a further drawback of the proof mass type system of power generation is the size of the proof mass is typically impractical for use on most embedded sensor systems.

[0005] Materials which can be attached to a vibration source and which generate an electrical current from the vibrations are known. Piezoelectric materials are examples of these materials, and are well known in the art. These materials generate small electrical currents when the material is deflected, for example by vibrations. A piezoelectric device which is small in size and advantageously utilizes the vibration energy of the platform as a power source is desirable. The use of very small devices such as micro-electro-mechanical systems (MEMS) is known in the art to generate power. However, they are either impractical due to the low power generated (i.e., typically in the microwatt range or as low as the nanowatt range) or unreliable compared with piezoelectric devices.

[0006] Piezoelectric crystal systems harvesting energy from the motion of humans or animals are also known. This type of a device is disclosed in United States Patent 3,456,134 issued to Kuo. Although the energy harvested by such a device may be adequate for remote sensing applications, it is 5 macroscopic in size, measured in inches, which is undesirable for most embedded sensing systems.

[0007] The improvement using a piezoelectric bimorph beam to harvest vibration energy is also known. A bimorph beam is herein defined as a mirror image double layer of piezoelectric material arranged in beam formation. A 10 bimorph beam is created by joining two oppositely polarized piezoelectric materials in a face-to-face configuration such that deflecting or bending the bimorph structure in one direction creates an electrical potential, and bending the structure in the opposite direction creates an equivalent electrical potential. The bimorph structure therefore produces electric current when deflected in either of 15 two directions. However, most known bimorph piezoelectric beam configurations to date have been on larger size beam configurations, and thus cannot be deployed in a thin conformal layer that can be attached to an arbitrarily shaped structure without adding significant weight or volume.

[0008] An improvement is therefore desirable for piezoelectric material 20 bimorph systems such that the resulting configuration is able to produce reasonably high current levels, while at the same time can provide a piezoelectric bimorph beam system which provides a degree of flexibility or conformability such that the material can be applied over a variety of surface areas, i.e. flat as well as curving surface areas. Also, past implementation of piezoelectric beams 25 either have not had adequate protection so that the beam does not break or get

damaged over a very long time period (tens of years) in a very harsh environment (e.g., aerospace) or they have had rather bulky and impractical protective packages.

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## SUMMARY OF THE INVENTION

[0009] According to the principles of the present invention, large arrays of MEMS devices having weighted, cantilevered, piezoelectric beams in a bimorph configuration, oscillate and produce electrical current from vibrations of the surface to which they are attached. The piezoelectric power source of the 10 present invention can be integrated in a variety of applications, including wireless sensor modules. The power devices of the present invention are capable of operation as part of a stand-alone unit that can last for the lifetime of a system, a time span measured in decades. The magnitude of energy needed for exemplary wireless sensor applications require a generation rate of milliwatts of power. This 15 is achieved in the present invention by maximizing the amount of energy each MEMS element generates and by using a large array of elements.

[0010] The power source devices of the present invention are made of the following parts: (1) an element – a weighted, cantilevered MEMS piezoelectric bimorph beam; (2) a unit cell – a collection of MEMS elements in a 20 form of about 1 centimeter squared ( $\text{cm}^2$ ) in area and about 0.5 millimeters (mm) thick, having about 150 to about 200 elements; (3) an array – the collection of many unit cells, typically about 100, all interconnected electrically to form a power generation unit; and (4) a protective sheath – a partially flexible electrically conductive material which forms a protective envelope for the unit cells on at 25 least one element side and which provides the interconnection pathways

between each element and the array. The sheath in one embodiment also provides a boundary limit, so that each piezobimorph element beam cannot overextend under impulse conditions, which could result in fracture. The sheath is preferably perforated, but can also be totally solid for some applications. The  
5 sheath is preferably flexible to permit an array to be connected over a flat or a contoured surface. The use of the sheath also allows for the array of MEMS piezoelectric bimorph beams to couple to longer wavelength harmonic vibrations of the structure, in a collective mode pattern, due the fact that all the elements of the array are mechanically joined to the sheath on one end.

10 [0011] In one preferred embodiment of the present invention, a bimorph piezoelectric device is provided, comprising a plurality of micro-electro-mechanical-system (MEMS) piezoelectric beams. The plurality of MEMS beams is arranged as pairs of MEMS beams, each pair having a connecting end and a weighted end. Each of said pairs of MEMS beams is electrically and mechanically  
15 joined through its connecting end to at least one flexible electrically conductive sheath, to form a joined array of MEMS beams, each having its weighted end free to deflect. Each weighted end of said pairs of MEMS beams of said joined array is deflectable to produce an electric current proportional to a quantity of said pairs of MEMS beams, said electric current is collectable from each of said  
20 at least one electrically conductive sheath.

[0012] In another preferred embodiment of the present invention, a piezoelectric device for converting vibration energy to electric current is provided, comprising a plurality of pairs of oppositely polarized piezoelectric wafers deflectable to produce an electrical current. The plurality of pairs of wafers are  
25 each connected to a set of micro-machined elements. Each said set of elements

with said pairs of wafers form a bimorph, said bimorph being configured as a cantilevered beam. Each said cantilevered beam is mass weighted on a first beam end, and fixedly attached to at least one protective sheath on a second beam end. A plurality of said bimorphs on said at least one protective sheath  
5 form an array.

[0013] In yet another preferred embodiment of the present invention, a method for forming a horizontally configured piezoelectric electrical current generating device is provided, which comprises the steps of: (I) creating an initial sub-assembly by: (1) joining a piezoelectric material plate to an upper  
10 surface of a substrate; (2) micromachining a lower surface of said substrate to both form a plurality of masses supported by said piezoelectric material plates and retain a plurality of non-machined lower surface areas; (3) electrically bonding said plurality of non-machined lower surface areas to an electrically conductive protective sheath; and (4) cutting through said piezoelectric material  
15 to separate a plurality of individual cantilevered piezoelectric material beam lengths; and (II) constructing a mirror-image sub-assembly to said initial sub-assembly; and (III) connecting said mirror image sub-assembly to said initial sub-assembly.

[0014] In still another preferred embodiment of the invention, a  
20 method for forming a vertically configured piezoelectric electrical current generating device is provided, which comprises the steps of: (1) filling until dry a sacrificial plastic replica mold with a ceramic piezoelectric slurry to form a piezoceramic green body; (2) bonding a substrate to said piezoceramic green body; (3) heat curing the substrate and piezoceramic green body to both remove  
25 said plastic mold and expose a plurality of piezoceramic vertical beams; (4)

casting a resist over said beams along a top surface thereof; (5) aligning an X-ray exposure to create a plurality of recesses for an electrode structure and plating a metal in the recesses to metallize the piezoelectric beams; (6) flood exposing a remaining portion of said vertical beams; (7) spin-coating a thin negative resist 5 layer for electrical isolation between the piezoelectric beams and the metallic proof mass and spin-coating a metal filled, negative X-ray resist on the top surface to provide a cantilevered proof mass; (8) performing a second aligned X-ray exposure to separate said cantilevered mass into a plurality of cantilevered masses; and (9) stripping both a remaining portion of said negative resist and 10 said flood exposed resist to form a plurality of said cantilevered piezoceramic vertical beams, each having one of said plurality of cantilevered masses.

[0015] Further areas of applicability of the present invention will become apparent from the detailed description provided hereinafter. It should be understood that the detailed description and specific examples, while indicating 15 the preferred embodiment of the invention, are intended for purposes of illustration only and are not intended to limit the scope of the invention.

#### BRIEF DESCRIPTION OF THE DRAWINGS

[0016] The present invention will become more fully understood from 20 the detailed description and the accompanying drawings, wherein:

[0017] Figure 1 is a perspective view of a partial unit cell of MEMS piezoelectric cantilevered weighted beams of the present invention;

[0018] Figure 2 is an elevation view of an exemplary substrate block at the initial step of manufacture of the partial unit cell;

[0019] Figure 3 is the elevation view of Figure 2, further showing a first etching step producing trenches in the substrate;

[0020] Figure 4 is the elevation view of Figure 3, further showing removal of a masking material and depositing a sacrificial material in the  
5 trenches;

[0021] Figure 5 is the elevation view of Figure 4, further showing attachment of a piezoelectric layer metallized on both sides adjacent to the filled trenches;

[0022] Figure 6 is the elevation view of Figure 5, further showing  
10 application of a masking layer on a lower substrate face;

[0023] Figure 7 is the elevation view of Figure 6, further showing etching of the lower substrate face and formation of lower channels;

[0024] Figure 8 is the elevation view of Figure 7, further showing micro-machined channels from the lower substrate face to a depth of the sacrificial  
15 material;

[0025] Figure 9 is the elevation view of Figure 8, further showing attachment of a flexible sheath having electrically conductive traces disposed on it;

[0026] Figure 10 is the elevation view of Figure 9, further showing  
20 multiple cuts through the piezoelectric beam layer;

[0027] Figure 11 is the elevation view of Figure 10, further showing a mirror image element assembly attached at each outwardly exposed piezoelectric beam layer of the Figure 10 initial assembly;

[0028] Figure 12 is a perspective view of a partial unit cell of the  
25 present invention showing a perforated upper and lower sheath;

[0029] Figure 13 is a perspective view of an alternate preferred embodiment of the present invention having vertically disposed MEMS members;

[0030] Figure 14 is an elevation view of a mold insert having an embossed or injected plastic sacrificial replica mold thereon;

5 [0031] Figure 15 is an elevation view of the plastic sacrificial replica mold of Figure 14, showing the mold cavities filled with a ceramic piezoelectric slurry to form piezoceramic beams, and a separate ceramic body attached to exposed surfaces of the piezoceramic beams with conductive traces present at the base of the beams;

10 [0032] Figure 16 is the rotated elevation view of Figure 15 after removal of the plastic molded material by a heat/curing process, showing a plurality of vertical piezoceramic beams;

[0033] Figure 17 is the elevation view of Figure 16, further showing a photo-imageable layer molded over the vertical beams of Figure 16;

15 [0034] Figure 18 is the elevation view of Figure 17 showing a plurality of recesses formed after an aligned x-ray exposure photolithographic process with a plurality of electrical contacts at the base of the beams used for metal plating;

20 [0035] Figure 19 is the elevation view of Figure 18, further showing a metal filler material plated within the recesses evacuated by the photolithographic step shown in Figure 18;

[0036] Figure 20 is the elevation view of Figure 19, further showing a spin coated, metal-filled x-ray resist on top of the substrate which forms the cantilevered mass; and

[0037] Figure 21 is an elevation view showing a portion of a unit cell of vertical elements of the present invention, following etching to remove all plastic material.

5 DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0038] The following description of the preferred embodiments is merely exemplary in nature and is in no way intended to limit the invention, its application, or uses.

[0039] Referring to Figure 1, a MEMS partial unit cell 10 is shown.  
10 Partial unit cell 10 comprises a plurality of piezoelectric cantilevered beams 12. At a fixed or support end of each of the piezoelectric cantilevered beams 12, an intermediate upper column 14 and an intermediate lower column 16 are provided. At a distal end of each piezoelectric cantilevered beam 12, an upper cantilevered mass 18 and a lower cantilevered mass 20 are provided. The upper and lower  
15 cantilevered masses 18 and 20, respectively, are provided to lower the resonant mode of the relatively short and stiff piezoelectric cantilevered beam 12.

[0040] When attached to a vibrating structure or item, the partial unit cell 10 will vibrate in response to the vibration source. The upper cantilevered mass 18 and the lower cantilevered mass 20 will deflect in the mass direction of  
20 motion arrows A as shown. For a horizontal element configuration shown in Figure 1, each of the intermediate columns 14 and 16, respectively, are attached to a flexible, electrically conductive sheath. In the configuration shown, the intermediate lower column 16 is attached to a lower sheath 24 by electrically conductive adhesive 22. Similarly, the intermediate upper column 14 is  
25 supported to an upper sheath (not shown) by the electrically conductive adhesive

26. Current generated by any of the individual piezoelectric cantilevered beams 12 is transferred via each intermediate upper column 14 and the intermediate lower column 16 to either the lower sheath 24 or the upper sheath (not shown). A plurality of MEMS elements 28 will make up a cell unit.

5 [0041] Referring now to Figure 2, a substrate 30 from which an individual group of MEMS elements 28 are formed is shown in the initial stage of construction. The substrate 30 is preferably made from one of the refractory metals such as tungsten, molybdenum, tantalum, or titanium. At this initial step, 10 the substrate 30 is provided with a photo-resist masking pattern 32 which is subsequently used in a photolithography process to trench the substrate upper surface 34. The photo-resist masking pattern 32 is attached as known in the art and will not be discussed further herein.

15 [0042] Referring to Figure 3, a plurality of individual trenches 36 is shown, which are etched in the substrate 30 by a photolithography process. The photo-resist masking pattern 32 provides the outer boundaries of each trench 36.

20 [0043] Referring to Figure 4, the photo-resist masking pattern 32 from Figure 3 is removed and a sacrificial material 38 is filled into each of the previously etched trenches 36. The sacrificial material 38 is filled up to the level of the substrate upper surface 34 of substrate 30 as shown. The sacrificial material 38 is typically an aluminum material but may comprise other metals or other materials as desired.

[0044] Referring now to Figure 5, following addition of the sacrificial material 38, a piezoelectric wafer 40 is attached to substrate 30 at the substrate upper surface 34. The piezoelectric wafer 40 is attached to the substrate 30

following a suitable metallization deposit (not shown) between the substrate upper surface 34 and the piezoelectric wafer 40 as known in the art.

[0045] The piezoelectric wafer 40 comprises a central layer of a piezoelectric material 42 surrounded by individual layers of metallization film 5 including a lower metallization film 44 and an upper metallization film 46. The piezoelectric material 42 preferably is a piezoelectric material with a high coupling factor, such as lead-magnesium-niobium-titanate (PMNT). The lower metallization film 44 and the upper metallization film 46 are preferably comprised of an electrically conductive solder-type material. By heating the metallization 10 deposit on the substrate upper surface 34 and the lower metallization film 44 of the piezoelectric wafer 40, the connection between the piezoelectric wafer 40 and the substrate 30 is made. The lower metallization film 44 can also be a conductive epoxy.

[0046] Prior to applying metallization layers on the piezoelectric 15 material 42, the piezoelectric material 42 is first poled. Poling is a process known in the art which applies a very high value electric field together with elevated temperature to align the molecules in a single direction in the piezoelectric material 42. Poling is preferably performed prior to bonding the piezoelectric material 42 because the poling process requires the addition of heat 20 (approximately 600°C for ceramic piezoelectrics) which is undesirable after the piezoelectric wafer 40 is formed. Subsequent deflection of piezoelectric material 42 creates a positive-to-negative charge separation distance which creates a voltage or potential between any two points of the material. This voltage is extracted as current by connecting the material through a resistor or electrical

load device. The voltage and therefore the current produced is proportional to the amount of pressure/ bending applied to the piezoelectric material 42.

[0047] Referring now to Figure 6, a further photolithographic process is performed by first applying a photo-resist masking pattern 48 on a substrate 5 lower surface 50 of the substrate 30. Similar to the process of Figure 2, the process initiated in the step shown by Figure 6 is used to etch trenches (see Figure 7) in each of the sections between the raised features of the masking pattern 48.

[0048] Referring now to Figure 7, a plurality of trenches 52 is shown 10 following etching between the raised features of the photo-resist masking pattern 48 attached to the substrate 30.

[0049] Referring now to Figure 8, each portion of the photo-resist masking pattern 48 shown in Figure 7 is removed to expose the substrate lower surface 50. A micromachining process is performed in each of the micro-machined areas designated with arrow B to remove material to a depth of, but not 15 including the areas of the sacrificial material 38. By removing material in the micro-machined areas B, individual intermediate columns are formed. A first intermediate column 54, a second intermediate column 56 and a third intermediate column 58 are formed by this micro-machining process. In addition 20 to the intermediate columns 54, 56, and 58, respectively, a group of weighted masses is also formed. A first weighted mass 60, a second weighted mass 62 and a third weighted mass 64 are shown. For clarity, Figure 8 shows only three exemplary intermediate columns and three exemplary weighted masses, however a plurality of such columns and masses are constructed to form a unit 25 cell. Each of the intermediate columns 54, 56, and 58, as well as each of the

weighted masses 60, 62 and 64 are comprised of the material of the substrate 30. The sacrificial material 38 is retained in the step shown in Figure 8 to protectively support each of the structures shown prior to completion of the attachment and micro-machining processes.

5 [0050] Referring now to Figure 9, the resulting structure shown in Figure 8 is attached to a conductive sheath 66 at distal ends of each of the intermediate columns. The first intermediate column 54 is joined to the conductive sheath 66 via a first conductive adhesive area 68. The second intermediate column 56 is joined to the conductive sheath 58 via a second conductive adhesive area 70. The third intermediate column 58 is joined to the conductive sheath 66 via a third conductive adhesive area 72. The conductive adhesive used to join the intermediate columns to the conductive sheath 66 is preferably an electrically conductive epoxy material, which is selected to provide sufficient stiffness to transfer the vibration energy of the vibration source (not shown) through the conductive sheath 66 to each intermediate column with low energy loss and small frequency change.

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[0051] Referring to Figure 10, a micro-machining step is next performed. Micro-machined (cut) areas identified by arrows C are shown between each successive weighted mass and its adjacent intermediate column. The portion of the sacrificial material 38 which is immediately below the section of the piezoelectric wafer 40 prior to this step (see Figure 9) is also removed by this micro-machining process. Each micro-machining cut is preferably performed using either a laser machining or a semi-conductor wafer saw process to separate the piezoelectric wafer 40 into individual cantilevered beams. A first cantilevered beam 74, a second cantilevered beam 76 and a third cantilevered

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beam 78 are shown in Figure 10 following the removal of material by the micro-machining process. Note that the sacrificial material 38 is retained in the step shown in Figure 10 in order to retain the structural rigidity between each of the weighted masses 60, 62 and 64 and the underside of each of the cantilevered  
5 beams 74, 76 and 78 respectively. These layers of the sacrificial material 38 are removed in a later step.

[0052] Referring now to Figure 11, a partial unit cell 86 is shown. The partial unit cell 86 is constructed by using an initial sub-assembly 88 provided by the step of Figure 10 and adding to this a mirror image sub-assembly 90 which is  
10 the mirror image of the initial sub-assembly 88. The mirror image sub-assembly 90 is constructed using the same techniques and steps as that for the initial sub-assembly 88 and is therefore not described in detail herein. As described below, conductive metallization layers (similar to those applied in the step described in Figure 5) are shown in exaggerated thickness between each of the cantilevered  
15 beam pairs.

[0053] A conductive sheath 92 forms an upper surface for the partial unit cell 86, and the conductive sheath 66 forms a lower surface for the partial unit cell 86. The initial sub-assembly 88 and the mirror image sub-assembly 90 are joined at the junction between cantilevered beams. As shown in Figure 11,  
20 the first cantilevered beam 74 of the initial subassembly 88 is joined to a fourth cantilevered beam 94 through a first conductive metallization layer 80. The second cantilevered beam 76 is joined to a fifth cantilevered beam 96 through a second conductive metallization layer 82. The third cantilevered beam 78 is similarly joined to a sixth cantilevered beam 98 through a third conductive  
25 metallization layer 84. After alignment of each of the paired cantilevered beams,

a heating process known in the art as solder-reflow is applied to physically join the initial sub-assembly 88 to the mirror image sub-assembly 90 via the conductive metallization layers 80, 82, and 84 respectively.

[0054] Following the step of joining each of the groups of cantilevered beams, the remaining sacrificial material 38 (previously retained in Figure 10), is removed from each of the spaces adjacent to each cantilevered beam and its associated weighted mass, i.e., in the areas identified as material removal areas D. The sacrificial material 38 is removed by an etching process. An outer facing surface of either the conductive sheath 66 or the conductive sheath 92 can be joined to a vibrating structure or body (not shown) through the use of a suitable adhesive or other joining method. The partial unit cell 86 is flexible to allow the conductive sheath 66 or the conductive sheath 92 which is attached to the vibrating body to conform to either a generally flat or a moderating surface of the body.

[0055] Electrical current generated by any of the cantilevered beams is passed via its associated intermediate column through its connecting adhesive area to its associated conductive sheath. Electrical current is collected from both the conductive sheath 66 and the conductive sheath 92.

[0056] Referring to Figure 12, a perspective, cut-away view of a unit cell 100 is shown. The conductive sheath 66 and the conductive sheath 92 of the unit cell 100 are also shown. A plurality of apertures 102 are formed in each of the conductive sheaths 66 and 92. The apertures 102 are optionally provided for an etching solution to remove the sacrificial material remaining on any portions of the unit cell 100. Figure 12 also shows a continuous intermediate column 104 that is preferably used in place of individual intermediate columns (e.g.,

intermediate column 16 of Figure 1) for a more efficient structural joining of a plurality of elements of the unit cell 100. A typical mass to mass spacing identified by arrows E is shown. The mass to mass spacing ranges from about several micrometers to about 100 micrometers. A typical mass to column spacing identified by arrows F is also shown. The typical mass to column spacing also ranges from about several micrometers to about 50 micrometers.

5       spacing identified by arrows F is also shown. The typical mass to column spacing also ranges from about several micrometers to about 50 micrometers.

Following element assembly as shown in Figure 12, each of the joined pairs of cantilevered beams form a bimorph beam 106. The bimorph beam 106 construction provides a double layer of piezoelectric material. Each layer half has

10      an oppositely polarized surface. By bending the bimorph beam 106 in either direction (as indicated by arrow A in Figure 1), an electrical current is generated.

[0057] Referring now to Figure 13, another preferred embodiment of the present invention is shown. Figure 13 shows a portion of a vertical element unit cell 200. Each vertical element 202 of the vertical element unit cell 200 is comprised of a vertical bimorph beam 204 and a unitary mass 206. For the vertical element unit cell 200, a single sheath 208 having conductive traces is used. The single sheath 208 is attached to the vibrating body inducing each of the vertical bimorph beams 204 to vibrate. Bi-directional motion indicated by arrows G is provided for each of the unitary masses 206. Each unitary mass 206 therefore forms the deflection limit for each successive vertical element 202. Vertical mass to vertical mass spacing identified as arrows H ranges from several micrometers to about 200 micrometers. The fixed end of each vertical bimorph beam 204 is electrically joined to the conductive traces of the single sheath 208 by construction as will be further elucidated with reference to Figures 14 to 19.

**[0058]** The process for forming the vertical element unit cell 200 differs from the process used to form the horizontal unit cell 100 of Figure 12. The following steps are used to form the vertical element unit cell 200.

**[0059]** Referring to Figure 14, the initial construction stage of a vertical 5 element unit cell is shown. A permanent mold insert 210, preferably constructed of nickel, is used as the receiving mold to develop a plastic sacrificial replica mold 212 having individual vertical beams. Alternate materials can also be used for the permanent mold insert 210. Either an embossing or an injection molding technique is used to prepare the plastic sacrificial replica mold 212 using the 10 permanent mold insert 210. The material for the plastic sacrificial replica mold 212 is preferably polymethylmethacrylate (PMMA) due to the material's photo-imaging properties using an electron beam, X-rays, or ultraviolet light. Other materials can be used for the plastic sacrificial replica mold 212.

**[0060]** Referring now to Figure 15, the plastic sacrificial replica mold 15 212 is shown following removal from the permanent mold insert 210. A slurry of piezoceramic material 214 is poured into each of the cavities of the plastic sacrificial replica mold 212. The top surfaces of each of the filled cavities of the plastic sacrificial replica mold 212 are polished after the piezoceramic material 214 solidifies. A plurality of metal conductive layers 215 is then deposited 20 through a mask (not shown) to the polished surfaces of the piezoceramic material 214. Since the deposition of a metal conductive layer is known in the art, it is not detailed herein. The material for the metal conductive layer is preferably a gold or gold containing material deposited using an evaporative or a sputtering step 25 also known in the art. A wafer 216 of ceramic or alternately of quartz material is then attached using a thin layer of a high temperature adhesive (not shown) to

the polished surfaces of the plastic sacrificial replica mold 212 and the piezoceramic material 214. The piezoceramic material 214 does not adhere to the material of the plastic sacrificial replica mold 212.

[0061] Referring to Figure 16, following the addition of the wafer 216,

5 as shown in Figure 15, the sub-assembly is heat cured which removes the plastic material, i.e., the plastic sacrificial replica mold 212 shown in Figure 15. The remaining material following this heat curing process is the arrangement shown in Figure 16 having the wafer 216 rotated 180° from the orientation shown in Figure 15, thus showing the vertical piezoceramic beams 218 in an upward facing 10 direction as viewed in Figure 16.

[0062] Referring now to Figure 17, a photo-imageable layer 220 is applied over the vertical piezoceramic beams 218. This photo-imageable layer 220 surrounds each of the vertical piezoceramic beams 218 and contacts the piezoceramic wafer 216. The photo-imageable layer 220 can advantageously be 15 applied up to a thickness of about 1 to 2 millimeters. Material for the photo-imageable layer 220 is preferably a PMMA material.

[0063] Referring to Figure 18, the remaining photo-imageable layer 220 from Figure 17 is shown after the top surfaces of each of the vertical piezoceramic beams 218 has been planarized to remove the excess photo-20 imageable layer 220 material. The excess material is removed to form a surface 222 indicated by arrow I. During this step, an aligned x-ray exposure is also performed to create a plurality of exposure recesses 224 down to a wafer surface 226 of the wafer 216 (installed in the step shown in Figure 15).

[0064] Referring to Figure 19, the exposure recesses 224 of Figure 18

25 are filled with an electrically conductive plating material 228 from each of the

electrical contacts 215 up to the surface 222 of each of the vertical piezoceramic beams 218. Material for the electrically conductive plating material 228 is selected from materials including nickel, copper, gold, and other electrically conductive materials. This is followed by a flood exposure step for the later  
5 removal of the resist pattern used for plating.

[0065] Referring to Figure 20, a metal filled, negative x-ray resist 230 is spin coated on the surface 222 to a predetermined height J. The predetermined height J is determined by at least one of the following: 1) the natural frequency modes of the vibrating body to which the vertical element unit cell or array is  
10 attached; 2) the number of elements of the vertical element unit cell; 3) the amount of electrical current desired; 4) the material/density of the mass elements; 5) the type of piezoelectric material used; and 6) the length of the piezoceramic cantilevered beams. Preferably, a plastic material is used for the negative x-ray resist 230. The plastic material should be a solvent-free plastic, such as epoxy,  
15 such that contact with the negative x-ray resist 230 will not effect the PMMA material of the photo imageable layer 220 remaining in the structure during this step. A photo-lithographic step is then performed to remove material from the negative x-ray resist 230, leaving open areas 232 to form a plurality of vertical unitary masses 234. Material for the vertical unitary masses 234 can be of metal,  
20 high density plastic, ceramic, or other material having a density suitable as a weighted mass.

[0066] Referring now to Figure 21, the remaining the PMMA material of the photo imageable layer 220 shown in Figure 20 is developed and stripped to form the final pattern of a partial unit cell 236 shown. A total vertical element  
25 height K ranges from about 0.1 mm to about 2.0 mm. The vertical element mass

width L ranges from about 0.1 mm to about 2.0 mm. To avoid electrical shorting between sections of the piezoceramic beam(s) if an electrically conductive material is used for the vertical unitary masses 234, an insulating layer (not shown) of a non-electrically conductive material is deposited between each 5 vertical unitary mass 234 and each vertical piezoceramic beam 218.

**[0067]** For applications using the vertical element design of the present invention, a protective cover can be used to prevent foreign material from entering between individual elements and to prevent physical damage to the exposed elements. The advantage of the vertical element design is that a greater 10 number of elements per square unit area is obtainable, therefore a potentially greater electrical current can be generated.

**[0068]** Currently, MEMS devices are generally constructed of micro-machined silicon. For the present invention, a refractory metal such as tungsten, molybdenum, tantalum, or titanium is preferably used for construction of the 15 element bodies. These materials provide better stiffness and much higher densities and thus are more suitable as proof mass material.

**[0069]** The piezoelectric MEMS devices of the present invention can be used as an electrical current source and attached to vibration sources which vary significantly. Examples of such vibration sources are any moving vehicle, i.e., 20 automobiles, aircraft, military craft and spacecraft. The devices of the present invention can also be used on a wide variety of other applications, such as being attached to clothing for generation of a small electrical power for hand-held electrical devices such as telephones. Another useful adaptation for the devices of the present invention is as a power source for remote sensing equipment. 25 Known sensing equipment used for remote sensing devices typically use

batteries or other electrical power generation sources such as chemical reactions. The piezoelectric devices of the present invention can be used to replace the battery or other power sources for remote sensor applications.

[0070] The bimorph configuration of the piezoelectric materials of the  
5 present invention is a preferred embodiment of the present invention. Poling of  
the piezoelectric material is preferably conducted prior to joining the two layers of  
material together to form the bimorph due to the elevated temperature of the  
poling process. The material is poled perpendicular to its thickness. The  
resulting piezoelectric material has a metallic contact plated on either side of the  
10 material to collect the electrical current.

[0071] The piezoelectric devices of the present invention offer several  
advantages. By configuring the devices into unit cells of varying numbers of  
elements, and with the ability to employ multiple unit cells in an array, a wide  
variety of electrical currents for varying power sources can be derived. The  
15 piezoelectric devices of the present invention are capable of being employed on  
flat or on varying geometry surfaces. These devices are relatively unaffected  
within a temperature range of about -60° centigrade to about 200° centigrade.  
The piezoelectric devices of the present invention also can operate essentially  
maintenance free for a significant period of time, i.e., several decades. There is  
20 no fuel source and there are no moving parts other than the degree of motion  
required for the cantilevered beams. The devices are pre-tuned based on the  
natural frequency modes of the item to which they are attached, such that  
spacing between each weighted mass of the elements of the device can be  
predetermined to preclude damaging the piezoelectric materials by over-  
25 extension. The piezoelectric devices of the present invention will generate

electrical current in the milliwatt range compared to devices known in the art which produce current in the microwatt or nanowatt ranges.

- [0072] The description of the invention is merely exemplary in nature and, thus, variations that do not depart from the gist of the invention are intended  
5 to be within the scope of the invention. Such variations are not to be regarded as a departure from the spirit and scope of the invention.